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A Review and Applicability Assessment of MEMS-Based Microvalve Technologies for Microspacecraft Propulsion

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A survey and evaluation of MEMS-based microvalves has been conducted to assess the applicability of this valve technology for propulsion applications on future microspacecraft. A variety of valve concepts has been reviewed, such as thermopneumatic, bi-morph, shape memory alloy, electrostatic, piezoelectric and electromagnetic concepts. All concepts were evaluated against a set of valve design requirements, assumed to be typical for future microspacecraft. None of the currently existing MEMS-valve concepts is able to meet all the requirements. Thermally actuated valves operate too slowly, whereas electrostatic valves, although offering fast actuation times, cannot provide the required sealing forces at reasonable voltage levels. Piezo-electric and electromagnetic actuation concepts offer the best potential for micropropulsion applications. However, currently available valve hardware is leaky and has poor pressure handling capabilities, as a result of the particular design solutions reviewed in these cases. Significant future development efforts will be required to make this valve technology applicable to microspacecraft propulsion systems. Areas of particular concerns are seat design and the ability of the valve actuation mechanism to provide sufficient seat pressures, integration of valves with driver and power conditioning electronics and material compatibility issues between MEMS-valve materials and liquid propellants. If successful, microvalves may enable the development of tightly integrated, micropropulsion modules which may be ideally suited for microspacecraft use.

I. INTRODUCTION

Microspacecraft concepts experience growing attention within the aerospace community. Several reasons may be named as the motivations behind this trend, such as reduced mission cost due to the use of smaller and cheaper launch vehicles needed for such microspacecraft, as well as the possibility to explore new and unique mission scenarios enabled by the use microspacecraft. For example, microspacecraft constellations charting entire regions of space may be envisioned. The measurement of particle and field distributions around a planetary object or even within the heliopause at the edge of our solar system may be performed more efficiently with such a constellation, providing a larger return of data than can be collected along the trajectory of a single larger craft.

Using such a "fleet" of microspacecraft, each spacecraft being equipped with its own set of experiments, will also increase mission reliability since the loss of one or even a few microspacecraft will not jeopardize the entire mission. Mission scenarios may be envisioned where small microprobes are released from a larger spacecraft to perform particularly risky parts of the mission. For example, probes may be released into Saturn's ring system to allow for a close-up survey of the system, while a larger craft serves as a communications node to earth, staying safely behind[1].

As a typical mass target for microspacecraft a few tens of kilogram or less are currently being envisioned. Spacecraft with a mass of 10 kg may be no larger than a "shoebox" or "basketball". Even smaller microspacecraft ranging in mass around 1 kg are being studied that in turn may be no larger than a "softball"[2]. Table 1 shows an attempt to classify microspacecraft and distinguish various degrees of miniaturization and integration required to realize them[3]. A photograph of a 7 kg ground demo functional model of one such microspacecraft design is shown in Fig. 1[4]. It shows the MTD (Microspacecraft Technology Development) II model that was assembled and ground-tested at the Jet Propulsion Laboratory (JPL). While the MTD II craft was not designed for spaceflight, it allows for testing of microspacecraft technologies and their integration in a hardware environment on the ground.

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Table 1: Definition and Classifications of Microspacecraft

Designation	S/C Mass (kg)	S/C Power (W)	S/C Dimension (m)	Comments
"Microspacecraft" (AF/European Definition)	10-100	10-100	0.3-2	Micropropulsion concepts beneficial due to weight/size savings, possibly enabling based on performance requirements (e.g. very small impulse bits for ultra-fine spacecraft pointing). Low end of mass range - see below.
"Class I Microspacecraft"	5-20	5-20	0.2-0.4	Use miniature "conventional" components, possibly MEMS/micro-fabricated. Conventional integration (e.g. feed lines) still possible, higher level of integration between components/subsystem desirable.
"Class II Microspacecraft"	1-5	1-5	0.1-0.2	MEMS/microfabricated components, high level of integration between components and subsystems required (subsystems on a chip?)
"Class III Microspacecraft" ("Nanosat")	<1	<1	<0.1	All MEMS/microfabricated. Very high level of integration between all subsystems and within subsystems required. Strong feasibility issues for masses substantially less than 1 kg at this time. Not considered in this study.

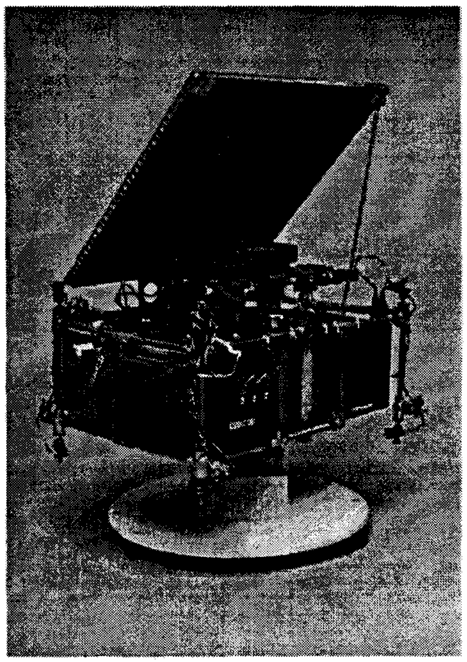

Fig. 1: MTD II Ground Demo Spacecraft Model[4]

In order to enable the construction of such microspacecraft, each subsystem will have to be reduced in size and adapted in function to meet the new and unique requirements of such a craft. For example, components of a micropropulsion subsystem for such a microspacecraft will have to be reduced in size to fit within the spacecraft envelope, requiring extensive miniaturization. Furthermore, thrust levels and impulse bits will have to be reduced. Thrust levels for attitude control of a microspacecraft may be on the order of a few milli-Newton or less and impulse bits as little as 10^{-6} Ns may be required. Thrust levels and impulse bits that low require the control of very small propellant flow rates. Microvalves will be required to control those flows.

Different microvalve concepts are currently under investigation. Conventionally machined, miniature solenoid valves are one valve option being studied at present. Several valve manufacturers in the US, such as Moog, Inc., Marotta Scientific Controls, and Kaiser-Marquardt, Inc., for example, have developed, or are in the process of developing, this type of valve and have achieved impressive degrees of miniaturization to date[5].

Paralleling efforts in other spacecraft sub-system areas, entirely microfabricated propulsion components, machined from silicon using Micro-electromechanical Systems (MEMS) fabrication techniques, have been studied recently[3]. Potentially significant additional mass and volume savings could be achieved if these microfabricated thruster components could be tightly integrated by chip-to-chip bonding with other MEMS-based components, such as valves, filters, regulators, sensors, etc., as well as the control electronics required to drive these devices. Apart from the potential of offering mass and volume reductions over conventionally integrated propulsion systems, such a highly integrated MEMS-based propulsion system would also have minimal external interfaces, easing and reducing the cost of integration of the propulsion subsystem into the microspacecraft bus. The latter point is of particular interest in the case of microspacecraft designs due to their small size.

Propulsion systems featuring such a high degree of miniaturization and integration will likely require suitably microfabricated MEMS-microvalve technology. Repeatedly, previously developed commercial MEMS-valves are being cited as examples of valves that may be applicable for use in such systems. In this paper, following a brief review of valve design requirements as currently assumed for microspacecraft propulsion systems, presently available MEMS-valves will be reviewed and evaluated in view of microspacecraft applications. As a result of this review, several technology needs will be identified, pointing to the requirement of substantial additional development efforts if this valve technology is to be considered a candidate for future micropropulsion designs.

II. MICROSPACECRAFT VALVE REQUIREMENTS

An attempt will be made in this chapter to present a set of representative requirements for valves suitable for use on future microspacecraft. Besides obvious restrictions with respect to size and weight, power consumption, voltage requirements, actuation time (defined here as the time to fully open the valve), as well as leakage, valve seating pressures and filtration requirements will need to be considered.

It should be noted that given the preliminary nature of microspacecraft designs no clear valve design guidelines have been established yet and many of the requirements listed will certainly be subject to further review as microspacecraft designs progress and become more concrete. Also, the set of requirements presented here is not complete. Mission specific requirements such as vibrational and thermal requirements are ill-defined at this point. In addition, without the knowledge of a concrete overall propulsion system lay-out, the requirements listed here will have to be somewhat generic.

However, despite these limitations, the list of requirements provided below may be considered adequate in the context of the scope of this study. As will be shown below, the specifications of many of the MEMS-valve types reviewed here are falling far out of the range of requirements listed in this chapter, so that the level of detail at which these requirements are presented here is thought to be sufficient.

Size and Weight

With current, conventional machining techniques it is possible to machine solenoid valves having a cylindrical envelope of about 1 cm in diameter and 1 to 1.5 cm in height. MEMS valve technology, even when individually packaged, should stay within this envelope. Current miniature solenoid valve masses are as low as about 10 gram. MEMS valves, fully packaged, should stay at least within this mass margin and hopefuly weigh significantly less. For MEMS valves, the package may easily weigh more than the silicon valve mechanism. Thus, weight savings for MEMS valve technology will most likely occur when several valves will be required to be assembled into a system and direct silicon-to-silicon bonding can be exploited in the integration of those components.

Power Consumption

Available power levels on microspacecraft will be severely limited. The power consumption of a microvalve should probably not exceed one to a few Watts. If possible, latching valve mechanisms should be explored that only require power during the actual opening or closing process.

Voltage

Typically, current spacecraft have bus voltages of 28 V. For microspacecraft, bus voltages are expected to be much lower. The MTD II design shown in Fig. 1 has a maximum bus voltage of ± 15 V. Voltages of no more than 5 V are expected in future microspacecraft designs. Microvalves to be used on such craft should be able to operate with these voltages. The possibility exists to provide MEMS-based transformer technology for valve actuation mechanisms that require higher voltages. However, in view of the size and weight constraints alluded to above, a tight integration of this power conditioning circuitry with the valve concept would be required in that case.

Minimum Valve Cycle Time

Minimum valve cycle times (defined here as the minimum time required to open and re-close the valve) are an important valve performance parameter for propulsion applications in view of minimum impulse bit requirements. Impulse bit is defined as

$$Ibit = \int_{t_{on}}^{t_{off}} F(t)\ dt \qquad (1)$$

where t_{on} and t_{off} are the times at which the valve opens and closes, respectively, and F(t) is the thrust force of the rocket engine, typically time dependent over a valve cycle. For microspacecraft applications, the impulse bit (Ibit) has to be minimized since otherwise the rate of turn of the spacecraft becomes too high, too many thruster firings will be required to maintain a certain dead band (pointing accuracy), thus wasting fuel, and the attitude of the spacecraft may be difficult to control. Impulse bit requirements as low as 10^{-6} Ns have been estimated in the past[3]. Again, these estimates are to be considered preliminary at this point.

If the thruster can be scaled down to provide a thrust level of 1 mN, valve cycle times of 1 ms must follow given Eqn. (1), assuming a constant thrust level over the valve cycle for sake of simplicity of the argument at this point. Valve cycle times of 10 ms and less are typical for fast acting miniature solenoid valves today. Using MEMS technologies, nozzle throat diameters can likely be scaled down to a point where only a fraction of a milli-Netwon can be provided, so that valve cycle times in the range of 1 - 10 ms appear acceptable.

Even longer valve cycle times will lead to even lower thrust requirements. Since attitude control thrusters are not only being used for dead band control, but may also serve to perform spacecraft slew maneuvers, potentially requiring much higher thrust levels into the one to several milli-Newton range for microspacecraft such as those considered in Table 1, this approach may not be very practical.

Pressure Requirements

Valve pressure requirements will be determined by the propellant tank (feed) pressure and the location of the valve in the feed systems. Assuming a maximum expected operating pressure (MEOP) equal to the tank pressure is a conservative estimate. Typical tank pressures for liquid systems may range up to around 300 psi, gaseous systems may require pressures up to several thousand psi.

Leakage

Every valve has a certain degree of internal leakage through the valve seat. For space-qualified valves on conventional spacecraft, leak rates of about 10^{-3} - 10^{-4} scc/sec GHe (gaseous helium) have been found adequate. In general, leak rate concerns are much more severe for gaseous than for liquid propellants. Leak rate requirements will also be more severe for microspacecraft than for conventional sized craft. This is due to the fact that the overall propellant supply onboard a microspacecraft will be limited. For a given mission profile (definined by the delta-v of the mission), the required propellant mass scales with the spacecraft mass

$$M_p \propto M_{S/C} \quad (2)$$

following the rocket equation. Furthermore, the propellant fraction x M_P lost due to leakage scales with the leak rate LR(t) and mission duration Δt

$$x\ M_p \propto LR(t)\ \Delta t \quad (3)$$

Here, the leakrate LR(t) may be a function of time due to the fact that propellant tank pressures may change and more contaminates may locate themselves on the valve seats as the mission wears on and more propellant has flown across those seats. Given Eqn. (2), Eqn (3) implies that the required leakage rate scales with the spacecraft mass. If a leakrate of 10^{-3} scc/sec GHe is acceptable for a conventional 500 kg class spacecraft. leakrates will have to be reduced to about 10^{-6} to 10^{-5} scc/sec for microspacecraft ranging in the 1 - 10 kg class to result in the same mass fraction of propellant lost due to leakage. If, on the other hand, the same leakage rate was to be maintained, a correspondingly larger fraction of the propellant would be lost due to leakage and consequently a larger amount of propellant would have to be loaded to offset this loss.

Achieving leak rates as low as specified with the limited actuation forces available for MEMS-valves will be an extraordinary challenge. Therefore, the estimations performed here may almost certainly imply the use of liquid propellants for long duration microspacecraft missions for which leak rates are substantially smaller than for gaseous propellants. Therefore, MEMS microvalves will likely have to be compatible with liquid propellants.

Valve Seating Forces

Internal valve leakage through valve seats can be reduced by increasing forces exerted by the valve mechanism onto the valve seat. In the case of soft seats, contaminants that may settle on the valve seat may be pushed deep into the seat material where they no longer can provide a leakage path, whereas in the case of hard seats stronger sealing forces may crush contaminates, thus reducing leakage. For conventional soft seat valves, valve seating pressures of several 100 psi to several 1000 psi for high pressure valve applications are typical. However, most presently available MEMS valves feature harder seats. For hard seat applications, seating pressures well in excess of 100,000 psi are desirable.

Given these requirements, and the limited actuation forces available for MEMS valves, using MEMS valves in space propulsion applications is sometimes regarded as a futile attempt. Note, however, that seating pressures, rather than total actuator forces are crucial in this application. Since MEMS does offer the opportunity to machine extremely narrow valves seats, seating pressures may be increased through a reduction of valve seating area alone. In addition, narrower seats will reduce the probability of contamination since less area of the valve will now be contamination sensitive.

Filtration

No clear design rules for filter rating determination exist. In general, the contaminant particle size has to be significantly smaller than the valve stroke and seat width, requiring adequate filtration upstream of the valve with a filter-rating correspondingly smaller than the seat width and valve stroke.

III. MEMS-MICROVALVE SURVEY

In this chapter, different MEMS valve technologies currently available or under considerable development will be reviewed, including MEMS valve mechanisms based on thermopneumatic, bi-morph, memory-alloy, electrostatic, piezoelectric, and electromagnetic actuation. Several pneumatic valve concepts also exist, however, are of considerable lesser interest for space applications since a separate gas supply would be needed to operate these valves, leading to system complexities and added weight. MEMS check valves have been fabricated, and may see use in specific applications. Normally-open valves have not been considered in this review since they will require power to be held closed, leading to high power consumptions over the course of a mission, and reliability concerns (loss of power will cause the valve to open).

Thermopneumatic Valves

Thermopneumatically actuated valves were first designed and built by Angell and Zdeblick at Stanford University in the late 1970's and early 1980's[6-8]. Later, Zdeblick founded Redwood Microsystems Corp. and sold this valve type commercially[8]. The principle of operation is illustrated in Fig.2. A liquid is trapped inside a cavity that is being formed by a recess in a silicon wafer and a Pyrex cover wafer anodically bonded to the silicon. The whole assembly is bonded to a glass substrate via a fulcrum joint fabricated into the silicon wafer. An electric heater, deposited onto the Pyrex wafer rather than the silicon wafer for better thermal insulation, heats the fluid to its boiling point. Virtually any fluid can be used and operating parameters of the valve will change with the choice of fluid. Redwood uses a class of so called 3M Fluorinert™ liquids with boiling points ranging between 56-253 C[8]. The increasing vapor pressure inside the cavity causes the thin silicon membrane to bow outward. This "ballooning" effect causes the poppet of the valve to raise off the seat, opening the valve. Besides the normally-closed valve design shown in Fig. 3, a normally-open valve has also been fabricated[6,7].

In theory this valve type can be used with any liquid or gas that is compatible with the valve materials

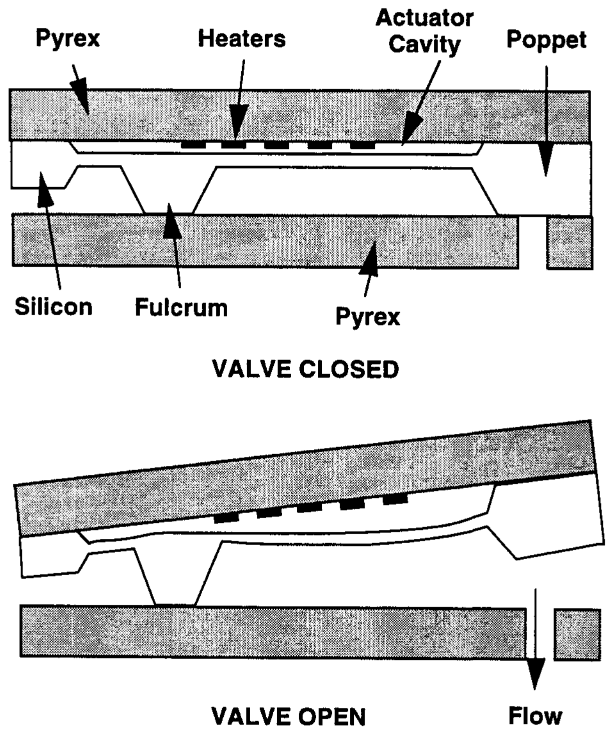

Fig. 2: Thermopneumatic Valve Concept. Figure adapted from Ref. 8.

used. However, heat transfer from the actuator cavity into a liquid propellant could have an affect on the operation of the valve, draining energy to heat and actuate the valve. Valve performances are listed in Table 2. Valve operation at pressures up to 3000 psi has been reported[6], however, for a normally-open valve. Up to 20 N actuation forces have apparantly been demonstrated in the case of such a normally-open valve version[6]. Normally-closed valve performance of 100 psi appear to be more typical[6,8]. Valve strokes of up to 150 μm can be reached[6] and power levels to open the valve range between 0.5 to 2 W[6,8]. The large valve strokes allow for considerable flow rate capability. Valves have been built that are able to handle up to 15 slpm N_2 at 100 psi[6], however, 2 slpm (2000 sccm) is a more typical flow rate[5]. Response time of the valve is slow, around 400 ms according to Ref. 8 at power levels of 2 W. Higher power levels will allow for faster valve actuation, however, as a result closing speeds are even slower due to longer times required to cool the valve. When packaged, the valve weighs about 4.5 gram and fits into a volume of 0.63 x 0.66 x 0.2 cm^3.[6,8]

Issues with this valve technology are its limited operating temperature range. A typical Redwood valve actuates around 50-60 C[8] limiting its operating temperatures to values less than that. As mentioned, actuator fluids with higher boiling points could be used which would extend the

Table 2: Typical Redwood Valve Performance Characteristics

Parameter	Representative Performance Data
Pressure (psi)	100 (3000 psi with NO valve?)
Power (W)	2
Weight (g)	4.5
Size (cm^3)	0.63x0.66x0.2
Response Time (ms)	400
Stroke (micron)	150
Flow Rate (sccm)	up to 15,000 sccm
References	6,8

operating temperature range of the valve, however, likely at the expense of higher power values to actuate the valve.

Another limitation of this valve is the use of silicon-to-silicon valve seats. Any contaminant that may locate itself on the seat may cause the valve to stay open and cause leakage. Unlike soft-seat materials, which may embed the contaminant particle, or hard seat materials, which would allow knife-edge seals to be fabricated to crush contaminants, the flat poppet in this valve, combined with the fact that no thermopneumatic forces are exerted in the closed state, appears relatively vulnerable to contamination. Note also that the cantilevered poppet movement does not provide a self-aligning seat design.

Attempts are underway at the California Institute of Technology[9] to address seat issues through the use of soft-seat silicon rubber. In devices explored at Caltech the actuator cavity is sealed with a silicon rubber membrane that has been molded in place[9]. Only a normally open valve has been manufactured so far. As the working fluid in the actuator cavity expands upon heating, the silicon rubber membrane expands until it touches the seat, sealing the valve. The valve was operated against 20 psi pressure at power levels as little as 0.28 W. Valve strokes were 100 µm[9] although the membrane is capable of significant larger deflections, "ballooning" up to 1-mm diameters[9]. Unfortunately, silicon rubber is permeable to the working fluids used in the experiments (ispropanol and PF5060, an industrial version of Fluorinert™). Future work thus focuses on proper sealing of the rubber material through additional coatings. Also, as mentioned, normally-open valve versions are of little interest in the space community.

Bi-morph Valves

Several different types of bi-morph valves have been explored to date and have been available commercially in the past. Hewlett-Packard[8,10] and IC Sensors[8,11,12] in the US and Robert Bosch GmbH[13] in Germany have conducted work with this valve type. The Hewlett-Packard concept is shown in Fig. 3 to illustrate the concept. Figure 3 is adapted from Ref. 10 This valve concept was developed by Barth[10]. It features a nickel-silicon bi-morph membrane actuator. Nickel and silicon membrane thicknesses are both between 25 - 50 µm. As can be seen by inspecting Fig. 3 more closely, the membrane is bend outward slightly in the closed position through the use of a central boss that is slightly higher than the sealing ring along the perimeter of the valve body, thus providing spring forces aiding in sealing the valve. The valve appears to have been fabricated through a series of anisotropic etches, combined with silicon fusion bonding steps and metal deposition sequences.

Actuation of the valve follows through passing an electric current through a heater, also made from nickel and deposited onto the membrane. As the membrane heats up, aided by the excellent thermal conduction through the silicon material, the nickel layer, due to its higher coefficient of thermal expansion, goes into tension and bends the membrane outward, thus opening the valve. Flow inlet occurs along the perimeter of the valve, through gaps in the membrane. The membrane design is elaborate, featuring torsion bars reducing force requirements to flex it.

The Hewlett-Packard valve has been operated at pressures up to 5-200 psi and flow rates between 0.1-1000 sccm[10]. Valve response times are around 100 ms[10], with total valve cycle times being larger, given by the time required to cool the valve. Power requirements are on the order of 1 W[10] and voltage requirements are up to 15 V to open[10] the valve at 100 psi. No leak rate information is given in the literature. Valve strokes are on the order of 50-100 µm[10]. The valve seat is small, featuring an only 20 µm wide rim surrounding a 200 μm^2 orifice[10]. The reasons for this design, however, are thermal in nature: by reducing the contact area between the membrane and the attached valve poppet (boss), heat losses into the remainder of the valve structure are minimized, reducing power requirements to actuate the valve.

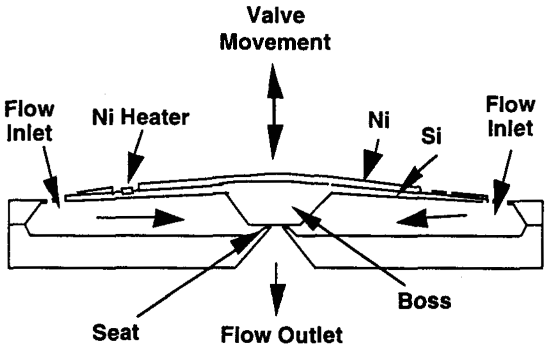

Fig. 3: Bi-Morph Valve, Hewlett-Packard Concept Figure adapted from Ref. 10.

Another bi-morph valve type was developed by Jerman at IC Sensors Corp[8,11,12]. The valve relies on the same principle as the Hewlett-Packard valve shown in Fig. 3. However, in the IC Sensors valve, the valve inlet is located off to the side of the membrane at one location along its perimeter. Flow exits the valve through the lower wafer, as in the case of the Hewlett-Packard valve. Membrane thickness is typically around 10 µm. A thick aluminum layer (5 µm) deposited onto the top silicon wafer forms a bi-morph structure with the underlying silicon membrane. In the IC Sensors valve design diffused doped silicon resistors inside the silicon membrane act as heating elements for the bi-morph membrane structure. As in the case of the Hewlett-Packard valve, the aluminum layer, due to its higher coefficient of thermal expansion (CTE), expands to a higher degree upon heating than the underlying silicon layer and goes into tension, thus bowing the membrane upward, raising the boss and opening the valve. Besides a normally-closed valve configuration, a normally-open valve has also been fabricated[12].

The IC Sensors valve has been operated at pressures up to 50 psig[11]. Reported leak rates are somewhat ambiguous. At 30 psi inlet pressure, leak rates of 3 x 10^{-4} scc/sec have been reported[11], while at 5 psi inlet pressures the reported leak rate was 5 x 10^{-4} scc/sec[11], i.e. larger than for the higher pressure value. Maximum flow rates of up to 150 sccm were reported[11]. Valve response times range between 100 to 300 ms to fully open the valve[11], depending on the power level. Additional time is required to close the valve by cooling, leading to total valve cycle times of about 250 - 450 ms[11]. Power requirements for this valve are given as 0.5 W[8]. Total package weight of the IC Sensors valve is 5.8 grams[8].

Both bi-morph valves, as the previously introduced thermopneumatically valves, suffer from the risk of unintended valve opening if valve temperatures raise to high, causing the bi-morph actuation mechanism to go into effect. A third bi-morph valve type was developed at automotive supplier Robert Bosch Company[13] in Germany. Here, two separate aluminum heater rings are deposited onto the silicon membrane as shown in Fig. 4. If the valve heats up due to ambient heat influx, both heater rings go into tension, causing the membrane to buckle without lifting the poppet off the seat. Actuation of the valve is achieved by just heating the inner ring, causing the same bi-morph actuation as in the case of the previously mentioned valves.

The Bosch valve has demonstrated flow rates of 5 sccm at 10-100 kPa pressure[13]. Power requirements for the valve are on the order of 1 W at the required flow rate[13]. Total valve cycle times are 100 ms, with the actuation time to fully open the valve being about 50 ms[13]. Note, however, the small valve stroke of only 8 µm for the valve. The valve chip size is 1 x 0.6 x 0.13 cm^3. All three bi-morph valves performances are listed in Table 3.

Shape Memory-Alloy Valves

Shape memory-alloy valves have been developed by Microflow and TiNi Alloy Companies[8,14-16]. Microflow no longer exists and the Microflow valve design, with some changes, is now being marketed by the TiNi Company[8]. A schematic of the valve design is shown in Fig. 5. The valve consists of three silicon wafers. The first silicon wafer features the valve seat and the valve outlet. The second wafer features the shape memory-alloy actuator and silicon poppet. The third wafer contains a silicon spring which pushed the memory-shape actuator and silicon poppet onto the valve seat in its closed position.

Table 3: Typical Performance Characteristics of Bi-morph Valves

Parameter	Representative Performance Data		
	Hewlett-Packard	**IC Sensors**	**Robert Bosch GmbH**
Pressure (psi)	5-200	1-50	0.15 - 15
Power (W)	1	0.5	1
Weight (gr)	5.8	5.8	-
Size (cm^3)	2.3x1.7x0.6	2.7x2.3x1.1	1x0.6x0.13
Response Time (ms)	100	100-300	50
Stroke (micron)	50-100	25	8
Flow Rate	0.1 - 1000	up to 150	5
Reference	10	8,12	13

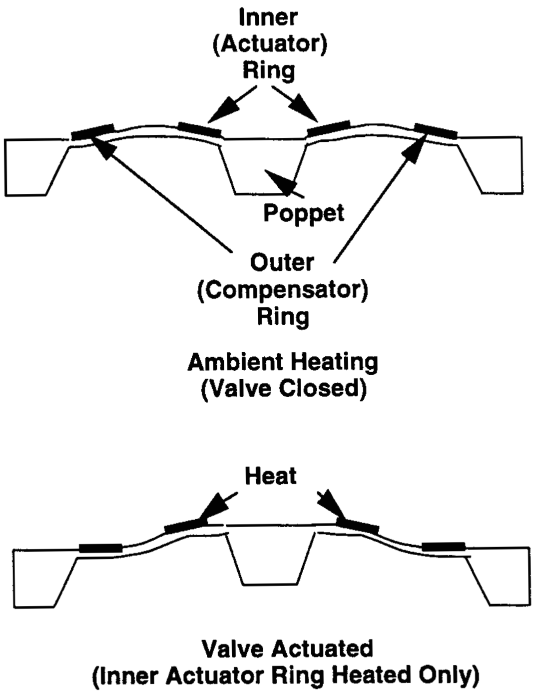

Fig. 4: Bi-Morph Valve Concept by Bosch with Thermal Compensation. Figure adapted from Ref. 13.

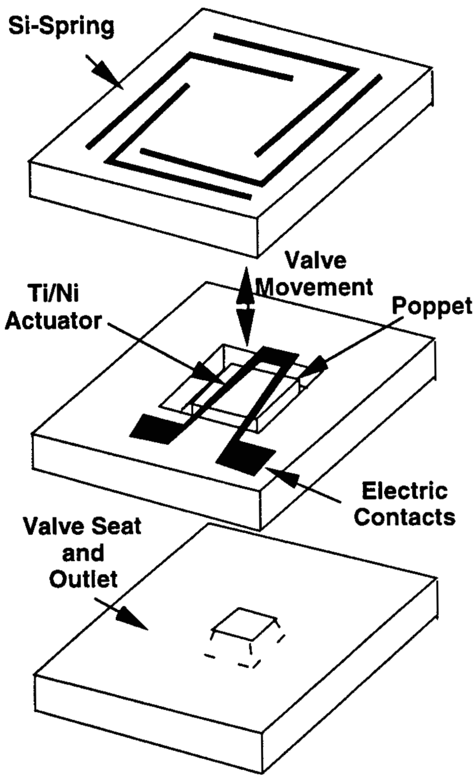

Fig. 5: Shape-Memory Alloy Valve Concept (TiNi Company). Figure adapted from Ref. 14.

Shape-memory alloy can be deformed plastically at low temperatures, as accomplished by the spring action in the valve shown in Fig. 5. Upon heating above its so called transition temperature, the alloy "remembers" its original, or parent, state and returns to this state. The parent state is established through a previous high-temperature anneal of the material during fabrication[15]. According to Ref. 15, the shape-memory actuator is formed by sputter-deposition from a nickel-titanium target. The resulting film then behaves like the bulk shape memory-alloy material. Heating of the Ti/Ni actuator is accomplished by passing a resistive current through it. Actuator film thicknesses range between 4 - 10 μm according to Ref. 15. The silicon spring returns the valve to its closed position after the current through the Ti/Ni membrane has been switched off.

Shape memory alloy valves have been operated at up to 100 - 400 psi inlet pressure[8,14], have achieved maximum flow rates of 6000 sccm and have response times of about 1ms to open and 20 ms to close[16]. Overall valve cycle times are larger again, due to the time required for cooling the valve, causing it to close. Power requirements are quoted at 0.3 -2 W[8,14]. Leak rates of 0.01 sccm have been measured[16]. Valve performances are listed in Table 4.

Electrostatic Valves

Several different types of electrostatic valves have been proposed. One of the more promising designs was developed by the Massachusetts Institute of Technology (MIT) in collaboration with the aforementioned Robert Bosch Company in Germany[17-20]. The Bosch Company is a major European automotive supplier and required a microvalve design suitable for use in hydraulic systems with a pressure handling capability of up to 15 MPa, or about 2000 psi[20]. The conceptual valve design is shown schematically in Fig. 6, adapted from Refs 17-19. The

Table 4: Typical Performance Characteristics of Shape-Memory Alloy Valves

Parameter	Representative Performance Data
Pressure (psi)	100-400
Power	0.3 - 2
Response Time (ms)	1 to open
	20 to close
Flow Rate (sccm)	up to 6,000
Leak Rate (sccm)	0.01
Reference	8, 14, 16

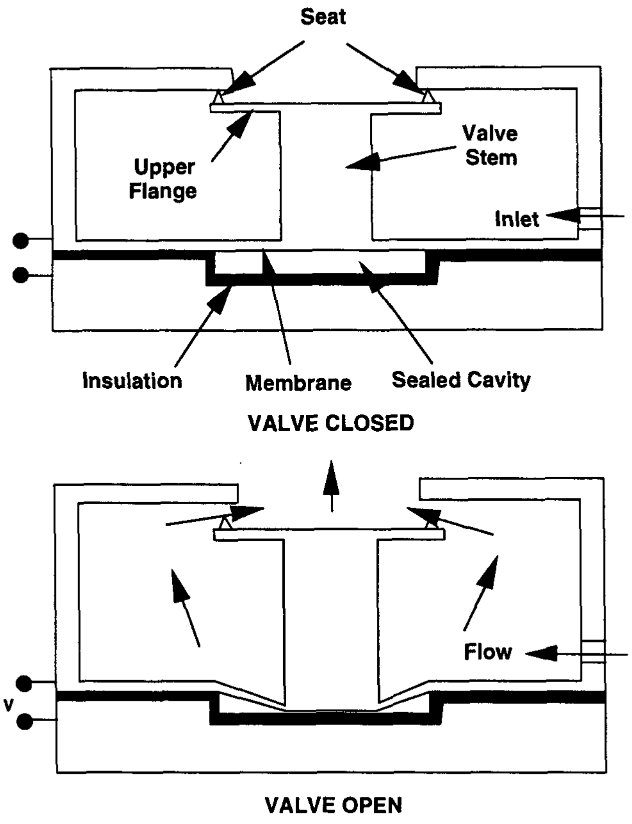

Fig. 6: Electrostatic Valve Concept by MIT/Bosch. Figure adapted from Refs. 17-19.

moving part of the valve is equipped with a flange featuring the valve seat. This flange is about equal in size (3 - 3.5 mm dia.) to the membrane to which the valve stem is attached. Pressure forces acting on the membrane, exerted by the fluid to be controlled, almost cancel each other with pressure forces acting on the flange. Thus, only small actuation forces are required to move the valve to its open position, even for relatively large fluid pressures.

As a result of this design approach, the cavity underneath the membrane may be evacuated. This is an important design feature in view of the electrostatic actuation of the valve. In the case of electrostatic actuation, a voltage difference is applied between the silicon membrane and the silicon substrate. Insulation between these two layers is accomplished by a thin silicon dioxide layer. Since the cavity is evacuated, electrostatic actuation of the valve is possible even when operating the valve with electrically conducting liquids. The shallow cavity limits the valve stroke to 5 µm, being the depth of the cavity.

Besides using an electrostatic actuation mechanism, the valve may also be pneumatically actuated by alternatingly pressurizing or evacuating the cavity. While this actuation mechanism may be suitable for the automotive industry, space-operated valve typically do not rely on pneumatic actuation due to system complexities and associated weight penalties.

This valve type has been successfully operated at pressures up to 60 psi, however, requiring actuation voltages of greater than 200 V. Since actuation is accomplished electrostatically, power consumption of this valve should be very low, determined only by small leakage currents through the insulating oxide layer and the applied voltage. However, no power values are given. Leak rates were estimated to be lower than 6 x 10^{-3} scc/sec at 35 psi[19]. Accurate determination of leak rates was not possible, however, due to measuring instrument limitations. Leak test data were obtained with a pneumatically actuated valve version[19]. Note that while the pressure-balancing effect allows the valve to be operated at greater pressures than may have been otherwise possible, the same effect also limits sealing forces of the valve since the pressure forces of the liquid are no longer being exploited to aide in sealing the valve.

Other electrostatic valve designs are given in the literature[21,22]. Figure 7 shows an electrostatic valve design by Hitachi, Ltd[21], developed for use in Molecular Beam Epitaxy equipment. Here, a thin, oversized Fe-Ni film is placed between two silicon wafers coated with an insulating silicon oxide layer. The silicon wafers contain two embedded electrodes. Since the Fe-Ni film is oversized, if forms an S-shape structure when placed between the two wafers. Applying an electrostatic potential to one of the two embedded electrodes while keeping the film grounded at all times, moves the film towards the electrode to which the potential has been applied. As a result, the S-shaped turn moves along the gap, opening or closing the valve (compare with Fig. 7). Applied voltages are on the order of 100 V and allow the valve to flow about 10 sccm at pressures of up to 1 atm, suitable for the intended application, but far out of the realm of applicable pressure parameters for space propulsion applications.

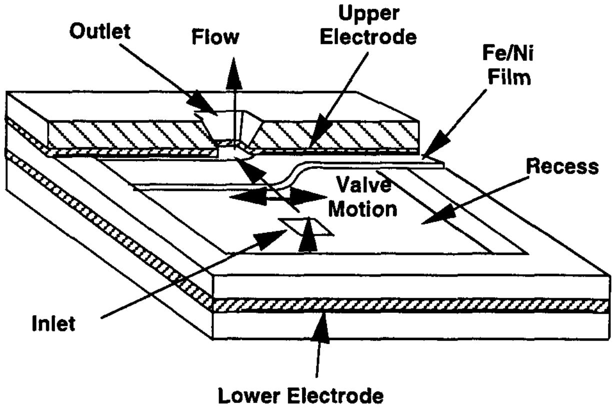

Fig.7: Electrostatic Valve Concept by Hitachi. Figure adapted from Ref. 21.

Several normally-open electrostatic valve designs also exist. One such design was developed by Ohnstein et al.[22] at Honeywell and is shown in Fig. 8. Here, a cantilevered beam is deflected by applying an electrostatic force between an electrode formed by a conductive layer embedded in the beam and another electrode embedded in the silicon material surrounding the seat. These metal electrodes are formed between silicon nitride passivation layers (shaded regions). Since the beam is formed through the removal of a sacrificial layer located between it and the valve seat, the valve is normally open and requires a constant force to bend the beam downward to close the valve.

The valve could be closed with 30 V applied against pressures of about 2 psi and held closed against pressures of about 14 psi. At a voltage of 30 V, valve leakage was 6 x 10^{-2} sccm. Both pressure handling capability and leakage are very poor in view of microspacecraft applications and a normally open valve concept, even considering the low power consumption (only a small leakage current flows between the electrodes), is not very useful for space applications since this valve would fail open in the case of a power failure.

Another normally-open electrostatic valve is mentioned here because of useful system aspects that were developed to ease its integration. Kluge et al.[23] at the Fraunhofer Institute for Solid State Technology in Germany provided their normally-open electrostatically actuated valve, relying on a similar principle of membrane deflection as in the case of the Ohnstein design, with an appropriate transformer circuitry. Even though the valve requires 200 V to actuate, the transformer circuitry only requires 5 V and provides the actuation voltage to the valve. Power consumption of the valve is 0.5 mW, with the transformer circuitry requiring another 72 mW. The valve operates at pressures up to 10 atm and is able to conduct flow rates of up to 700 sccm at these pressures[23]. The chip is 0.6x0.6x0.1 cm^3 in size. The valves are assembled on a wafer level using a low temperature silicon fusion bonding technique[23].

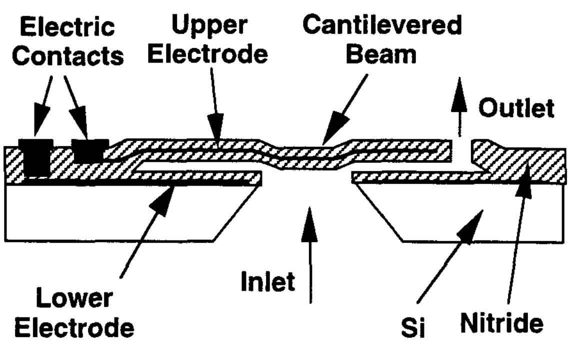

Fig. 8: Electrostatic Valve Concept by Honeywell. Figure adapted from Ref. 22.

All electrostatic valves are still in very early stages of their development. In can be noted, however, that even though the valves are fast (an advantage for space applications), electrostatic valves are unable to operate at very high pressure levels due to the limited forces that can be provided by electrostatic means and thus appear not very useful for space propulsion applications.

Piezoelectric Valves

A piezoelectric microvalve design by Esashi et al.[24] is shown in Fig. 9. The valve consists of a Pyrex wafer featuring the valve outlet and the valve seat, a silicon wafer, featuring a so called movable "valve mesa" and integrated knife-edge sealing ring, and the piezoelectric actuator mechanism. The piezoelectric actuators are connected to the valve body via a 9 mm long glass tube, bonded to the movable "valve mesa" using epoxy. The valve is normally closed and upon applying voltage to the actuator it contracts, thus pulling the movable valve mesa off the valve seat, opening the valve.

Piezoelectric actuation mechanisms are characterized by high voltage requirements comparable to those found for electrostatic valves. The type of piezo-electric valve described above requires between 50 - 100 V to open the valve, depending on pressure and flow rate. Flow rates through the valve were varied between 0.1 - 90 sccm by varying the voltage between 0 - 100 V at a pressure of 0.75 atm. At 0 V the valve leaks at flow rates of about 0.1 sccm or less, depending on pressure. In addition, the valve assembly, in particular the glass tube arrangement, appears fragile.

Other piezo-electric valves are currently being explored in Europe and in the US. At ACR Electronic

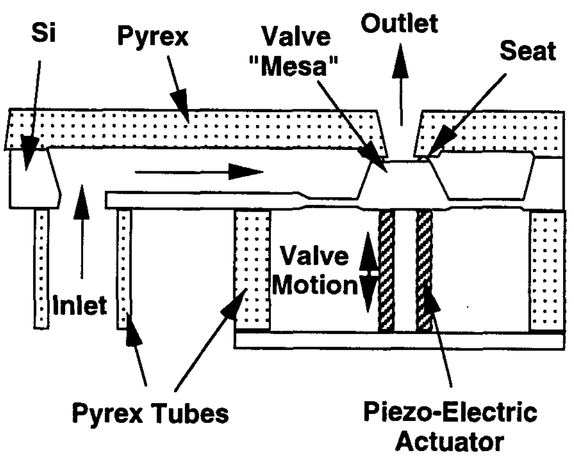

Fig. 9: Piezoelectric Valve Concept by Esashi et al[23]. Figure adapted from Ref. 24.

Company, in collaboration with Uppsala University, both in Sweden, piezoelectric microvalves are currently being studied under funding by the European Space Agency (ESA) for use as valves in a micromachined cold gas thruster quad[25-27]. This valve is still under development and no performance data are available yet. One option being explored in the Swedish study is the use of stacked piezo-electric actuators. Due to this stacking approach, the deflections of each piezo-electric element in the stack are additive, allowing large deflections to be obtained with much smaller applied voltages of only 25 V. An added benefit of this arrangement is that piezoelectric actuators provide more force at smaller deflections[12]. Since the deflection of each element is small, relatively high actuation forces may be obtained.

Figure 10 shows a schematic of this valve based on information provided in Ref. 25-27. As can be seen when comparing Figs. 9 and 10, the ACR/Uppsala piezoelectric valve[25-27] appears much more compact and robust than the valve by Esashi et al.[24]. The Swedish valve also relies on a silicon-membrane deflection effected by the piezo-actuator, causing a poppet connected to the silicon membrane to lift off the seat, thus opening the valve. A similar valve concept is also under development at JPL[28]. This activity is in its earliest development stages. One focus area in that study is the development of unique valve seat designs[28].

Electromagnetic Valves

Several different types of electromagnetically actuated valves were found in the literature[29-32]. However, due to current limitations of MEMS-machining techniques in providing a sufficient number of coil turns, these valve types typically use external coils or permanent magnets[29-32], resulting in MEMS-hybrid valve versions. One such type is shown in Fig. 11[29]. This valve type features a valve cap (poppet), integrated with a spiral-shaped spring, fabricated using Argon ion beam sputter-deposited thin film magnetic NiFe material. The spring is connected to the valve body, featuring the seat and the valve outlet. Flow enters the valve

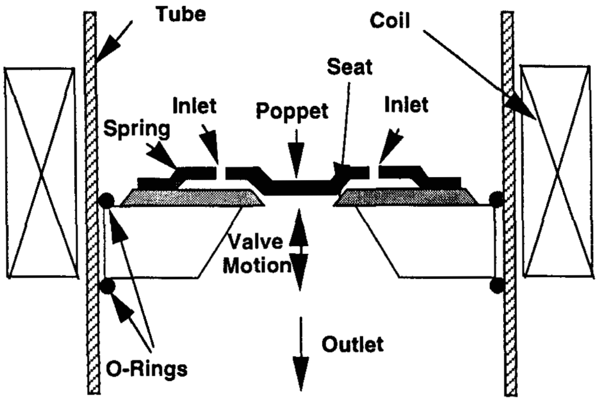

Fig.11:Electromagnetic Valve Concept by Yanagisawa et al.[29]. Figure adapted from Ref. 29.

through the spring. The valve is inserted into a tube and an electromagnetic coil is placed over the outside of the tube. The magnetic field of the coil interacts with the magnetic poppet and moves it up or down, depending on field and coil current direction.

The valve is fabricated using a sacrificial layer technique, leaving a gap between the poppet and the valve seat upon removal of this layer, resulting in a normally-open valve state. However, valve poppet and spring configurations can be fabricated where the Ni/Fe film experiences a compressive stress, achieved by properly adjusting the Argon ion beam energy in the sputter deposition process of the film. In this case, the poppet is pressed onto the valve seat in its non-actuated state (normally-closed). Actuating the coil will lift the poppet off the seat providing proper magnetic field direction.

As can be seen when inspecting Fig. 11, this valve requires a rather specific packaging arrangement, limiting its use in tightly integrated propulsion packages as discussed previously in this paper. Other valve concepts, based on a similar design approach, were developed by Pourahmadi et al.[30] and Smith et al.[31]. No performance data were found in the literature for either of these valve types.

Another electromagnetic valve type, more amenable to integration but still featuring a MEMS-hybrid design approach, was developed by Bosch et al.[32] of Daimler-Benz Aerospace (DASA), formerly known as Deutsche Aerospace. This valve type is one of very few MEMS-valves specifically developed for space applications (others are the Swedish and JPL piezoelectric valves). The DASA valve concept was targeted for use in an ion engine feed system. A schematic view of the valve is shown in Fig. 12.

The valve consists of a bonded wafer pair. The top wafer features the valve inlet and a recess about 10 μm deep. The recess wall is coated with a conducting electrode and an

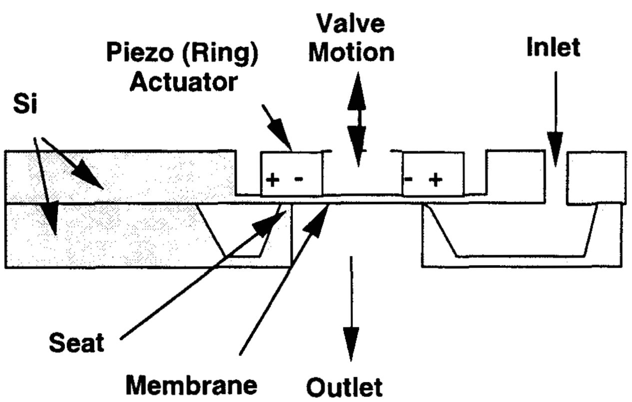

Fig. 10: Piezoelectric Valve Concept by Stenmark et al.[25-27]. Figure adapted from Ref. 25.

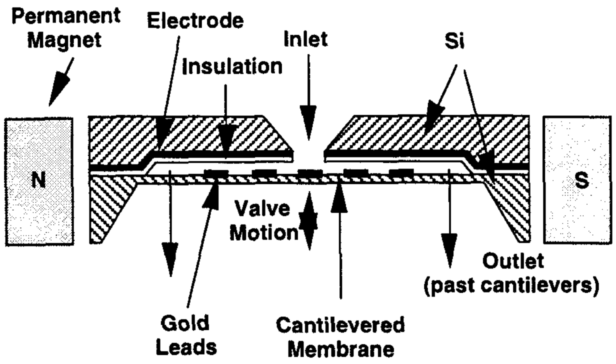

Fig.12:Elecromagnetic Valve Concept by DASA/Germany. Figure adapted from Ref. 32.

insulating layer (not specified). The lower wafer features a membrane suspended by four cantilevers. Gold-deposited current paths run along the top surface of the membrane, carrying a current pointing into or out of the plane of the paper in Fig. 12. This current interacts with a magnetic field provided by two strong, external permanent magnets which are placed next to the chip, not integrated with it. The resulting Lorentz-force will cause the membrane to move either up or down depending on current direction, thus closing or opening the valve. An electrostatic potential may be applied between the electrode coating the cavity wall and the conducting current paths on top of the membrane, thus holding the valve in a closed position.

As may immediately be suspected when inspecting the valve design, the weak electrostatic forces used to hold the valve in its closed position, in combination with the inlet flow impinging directly onto the membrane, lead to poor pressure handling capability. The valve can be operated against pressures of 160 mbar (about 2 psi) only and held closed with 30 V applied across the electrodes up to a pressure of merely 300 mbar (about 4 psi). Power requirements for this valve are low, however, ranging around 50 mW and voltage requirements have been limited to 30 V. Valve strokes are on the order of 10 - 15 µm and valve response times of less than 1 ms have been estimated.

Thus, although specifically designed with space applications in mind, this valve concept quite clearly does not meet this goal, with the exception of very low pressure applications. While the electromagnetic actuation mechanism is an interesting approach, relying on electrostatic forces to keep the valve closed severely compromises the valve design with respect to its pressure handling capability, in addition to providing a potentially severe failure mode as loss of power would cause the valve to fail open, causing propellant leakage.

Check Valves

Check valves allow flow in one direction, but block flow in the opposite direction without need for power to actuate the valve. The flow itself causes the valve to open or close. Check valves fit specific applications in propulsion systems, typically used in bipropellant systems upstream of the propellant tanks, preventing propellant vapors from migrating upstream into the pressurization system for these tanks, where fuel and oxidizer may mix and possibly lead to explosions. Check valves cannot replace command-controlled valves such as the valves discussed in previous chapters. Given that bipropellant systems, due to their complexity, high part count and associated weight and volume requirements may not be ideal candidates for microspacecraft systems, the development of MEMS-based versions of check valves may not be an urgent requirement for microspacecraft.

Briefly, MEMS-based check valves may follow very simple designs[33,34]. One concept is illustrated in Fig. 13. This valve features a spring-loaded, suspended membrane. If flow enters the valve through the top wafer, the membrane is pushed downward, away from the inlet and the valve will allow flow to pass through it, past the membrane suspensions. If the flow direction is reversed, however, the membrane will be pushed against a valve seat (in this case constituted simply by the flat silicon substrate surface of the top wafer in Fig. 13) and the valve will seal.

The concept shown is merely representative of others. In Ref. 33, for example, the concept is based on a cantilevered beam acting much in the same way as the suspended membrane of Fig. 13. The problem with a cantilevered beam approach is that the beam may not press evenly against the valve seat (not self-aligning) and gaps may form between the beam and the seat, allowing flow to pass even in the closed valve position. However, no leakage data were found for the cantilevered beam check valve concept[33].

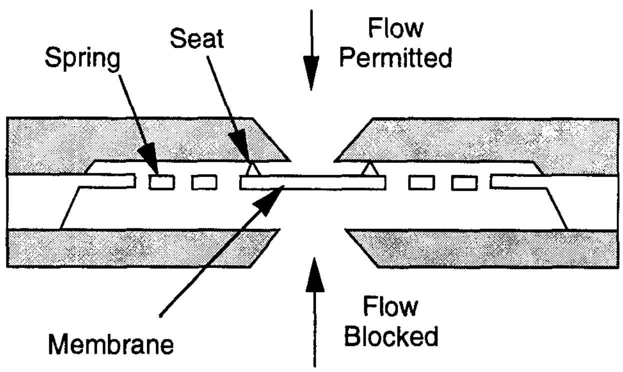

Fig. 13:Check Valve Concept.

Isolation Valves

Isolation valves, such as the commonly used pyro-valves used in conventional feed systems, are one-time opening valves (normally closed type) or one-time closing valves (normally open type). Thus, they cannot replace the function of a valve allowing for repeated actuation, but serve critical functions in a propulsion system nonetheless. Isolation valves serve to seal the propulsion system during launch, for example, where valves designed for repeated actuation may shutter, leading to leakage, or seal a propulsion system during long, inactive interplanetary cruises, providing zero leak rates.

A MEMS-based version of such an isolation valve is currently being developed at JPL[35,36]. This valve is silicon-based and fits on a chip 1x1x0.05 cm^3 in size. A photograph of an early valve prototype is shown in Fig. 14 and the valve concept is shown in Fig. 15. In this valve concept, flow is prevented from exiting the valve prior to actuation by a doped silicon barrier blocking the flow. This barrier is an integral part of the valve structure, machined by etching it into place and does not feature any seals that may be compromised through contamination or vibrations experienced by the valve. To actuate the valve, an electric current is passed through the narrow barrier (15 - 50 μm thick). As a result of the heat dissipation of the current passing through the barrier, causing it to melt, and the upstream propellant pressure, the barrier is blown away, opening the valve.

The micro-isolation valve is still in its earliest development phases and current emphasis is on proving the feasibility of the valve. Sufficient pressure handling capability, demonstration of valve actuation, and trapping of barrier debris within the valve body, avoiding the contamination of downstream flow components, are considered major milestones in proving the feasibility of this concept. Of these, the first two milestones have recently been accomplished. Valves have been fabricated featuring burst pressures of up to 3,000 psig[34] and valves were recently successfully fired, opening within less than 0.5 ms[36]. Valve debris was detected on the downstream side of the opened barrier, as expected, however this debris appears to stick to channel wall surfaces, a fact that may be exploited in the next crucial step of valve development, seeking to demonstrate debris trapping within the isolation valve body. A more detailed description of the results obtained may be found in a companion paper[36].

Pneumatic Valves

Work has been performed on a series of pneumatically actuated MEMS-based valves[37-40]. One of these concepts was introduced earlier, representing a version of the otherwise electrostatically actuated MIT/Bosch Company valve. However, as was noted earlier, pneumatically actuated valves are only of very limited interest to space applications as their actuating mechanism requires additional flow management, leading to system complexities and weight penalties. Therefore, pneumatically actuated valves were not considered in this study.

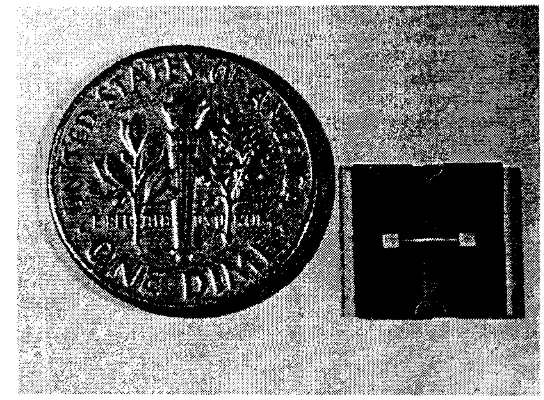

Fig. 14: Micro-Isolation Valve Test Chip

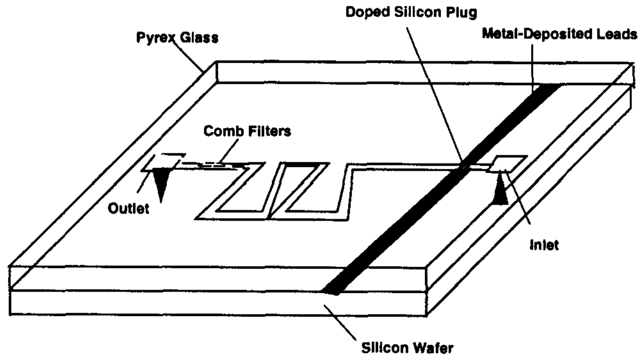

Fig.15: Schematic of the Micro-Isolation Valve Concept

IV. EVALUATION OF STATE-OF-THE-ART MEMS-VALVES AND FUTURE TECHNOLOGY NEEDS

Evaluation of State-of-the-Art Technology

In Table 5 the results of an evaluation of the MEMS-valve technologies reviewed here is given in view of microspacecraft propulsion applications. The evaluation is guided along the propulsion requirements for microspacecraft listed in Chapter II. Given the aforementioned preliminary character of these requirements, results of this evaluation are kept rather qualitative.

Prior to discussing the specifics of this evaluation, a few notes are in order, putting the results obtained in this evaluation in perspective. As a quick glance at Table 5 reveals, there appears to be no MEMS-valve technology existent today meeting all the evaluation criteria listed in Chapter II. This is not to be understood as a criticism of the

Table 5: Evaluation of MEMS Valve Technology for Microspacecraft Applications

	Thermo-pneumatic	**Bi-Morph**	**Shape Memory-Alloy**	**Electrostatic**	**Piezoelectric**	**Electromagnetic**
Size and Weight	Excellent	Excellent	Excellent	Excellent	Excellent	Excellent
Power	Good	Good	Good	Excellent	Excellent	Excellent
Voltage	Acceptable	Unknown	Unknown	Poor	Poor	Acceptable
Cycle Time	Poor	Poor	Poor	Excellent	Excellent	Excellent
Pressure	Marginal	Marginal	Marginal	Poor	Unknown	Unknown
Leakage	Poor	Poor	Poor	Poor	Unknown	Unknown
Seating Pressures	Acceptable	Acceptable	Acceptable	Poor	Good	Good

Ratings: Excellent, Good, Acceptable, Marginal, Poor valve technology surveyed. Each one of these valves represents a remarkable progress in miniaturization over technology available only a couple of decades ago. The technology produced is testimony to the creativity and originality of their respective innovators. However, most of these valves were designed with terrestrial applications in mind, ranging from tasks within the medical field, via semiconductor processing equipment to automotive applications. Space propulsion applications are unique and differ substantially in their requirements from those aforementioned applications, posing severe constraints on leakage, required actuation times, and robustness. It is therefore not surprising that state-of-the-art MEMS technology is lacking in regard to many of these design criteria.

Specifically, while most MEMS valves fairly easily match mass, volume and power requirements as defined in Chapter II, several (thermopneumatic, bi-morph and shape memory-alloy) do poorly with respect to valve actuation times, which would lead to long thruster on-times and wide impulse bits. These types of valves also suffer from the risk of un-commanded valve opening if the valve gets to hot due to ambient heating, initiating the actuation mechanism. Only one bi-morph design[13] addresses this latter issue.

Several valves have excellent response times (electrostatic, piezoelectric and electromagnetic valves). However, both electrostatic and piezo-electric valves have very high voltage requirements at their current stage of development, requiring dedicated power conditioning circuitry. Both electrostatic and piezo-electric valves offer only small valve strokes at the present time which may pose limitations to the use of the valve with very viscous fluids. Electrostatic valves also do very poorly with respect to providing adequate seating forces, resulting in severe concerns with respect to leakage and pressure handling capability.

Leakage concerns, however, are not limited to electrostatic valves alone. All valves considered here do relatively poorly with respect to leakage and rate at best marginally with respect to pressure handling capability, pointing to the need for improved valve seat designs.

Future Technology Needs

Given the current limitations of MEMS-valve designs with respect to microspacecraft propulsion requirements, new valve developments are clearly needed if this valve technology is to be applied for this application. While size, weight and power requirements currently pose no challenge when resorting to microfabrication methods, the following areas of concern stand out when seeking to improve current MEMS valve designs:

(1) *Valve Cycle Times* - In order to achieve fast valve actuation and cycle times, only piezo-electric or electromagnetic valve approaches appear appropriate at this stage. Thermally actuated valves are too slow and may overcome their limitations in this regard only to some extend during the opening cycle of the valve if high power levels are applied, shortening the opening cycle. In order to achieve short actuation times during opening, however, the actuator will have to be well insulated to cause rapid temperature increases. This in turn will lengthen the time required to cool and close the valve. Electrostatic valves, although fast, are unable to provide the required sealing forces. Thus, it appears that future MEMS-valve research activities, aimed at providing valves for micropropulsion applications, should target either piezoelectric or electromagnetic drives.

(2) *Seating Pressures* - Seating forces, or, more precisely, seating pressures of MEMS-valves need to be increased to reduce valve leakage and enable higher pressure operations. While piezo-electric actuators are known to deliver relatively high forces, these are typically only delivered over very short valve strokes. In the case of electromagnetic actuators the need to increase valve actuation forces immediately translates into high number of turns for the coil. Fabricating such coils using MEMS techniques may pose a major challenge. Note, however, that MEMS techniques also offer advantages that may be exploited to achieve high seating pressures. Using MEMS, very narrow valve seats can easily be fabricated, potentially resulting in large seating pressures even if actual seating forces are limited. Seat design, to be discussed next, will thus play an important role in future MEMS valve research.

(3) *Seat Design* - As discussed, seat design may aide in obtaining high seating pressures by resorting to very narrow, "knife-edge" seals. Narrower valve seats will also decrease the likelihood of seat contamination. "Knife-edge" seating techniques, however, will require the use of very hard materials and self-aligning seats to achieve good valve closure. Such "hard seat" techniques may provide enough seating pressure to crush contaminates, thus sealing the valve. Another approach maybe to resort to "soft-seat" designs. In this approach, the contaminates are not being crushed, as in the previously described hard seat design, but instead are being embedded in the seat material. One of the soft-seat technologies currently under investigation is the use of silicon rubber materials[9,37,40]. Silicon rubber has shown excellent adhesion to silicon and silicon nitride. One of the problems encountered with silicon rubber material is its permeability with respect to various liquids. Studies are underway to develop composite membranes using silicon rubber and appropriate sealing films[9].

(4) *Integration Aspects* - Future microvalves may have to be tightly integrated with other components in

micropropulsion feed systems. This is either due to the desire to achieve very compact propulsion modules, requiring the integration of various flow components such as thrusters and filters with valves, or due to the need to provide actuation voltages that may exceed microspacecraft bus voltages, requiring power conditioning chips to be integrated with the valve chips. Piezo-electric valves, for example, typically require voltages in the range of 100-200 V. Even electromagnetic actuators, due to large wire lengths and small wire diameters, may have considerable resistances and thus voltage requirements possibly exceeding the capability of microspacecraft. The integration of power conditioning circuitry with the valve body on a chip level may still allow for an extremely compact microvalve structure to be realized without requiring excessive design compromises in the actuation mechanism, increasing valve design flexibility.

(5) *Material Compatibility* - Microvalves, due to the use of microfabrication approaches in their construction, may face unique material compatibility issues between the materials of construction and propellants used. This will particularly be the case for silicon-based microvalves and such propellants as hydrazine, for example. Silicon may be used for reasons of microfabrication heritage and ease of integration between flow components and power conditioning electronics, while hydrazine has traditionally been used for many attitude propulsion applications, and may continue to be used for primary propulsion applications on microspacecraft as well[3]. An attitude control system may benefit when using the same propellant as the primary system, eliminating the need for additional propellant tanks. In cases such as these, detailed material compatibility studies will be required and special erosion resistant coating techniques (i.e. silicon dioxide), as well as the use of new MEMS materials may have to be explored.

V. CONCLUSIONS

State-of-the-art MEMS-valve technologies were reviewed in view of microspacecraft propulsion applications. The MEMS-valves were evaluated against a set of requirements defined in this study. None of the valve types considered met all the requirements. This is due to the fact that virtually all MEMS-valve technologies existent today were developed for terrestrial applications, either in the medical field, or semiconductor and automotive industries, to name but a few. Space propulsion requirements are unique and pose severe challenges with respect to valve leakage, actuation times, seating forces and pressure handling capability. MEMS-valves considered for space propulsion will also have to meet severe mass, volume and power constraints, which, however, are already being met by many commercially available microvalves today.

Piezoelectric and electromagnetic valve actuation mechanisms appear to be the most promising approaches to date due to achievable fast valve actuation times. However, presently available valve technology based on these actuation mechanisms is severely lacking in regard to leak rate and pressure handling requirements and will require significant additional development efforts to be suitable for use in microspacecraft propulsion systems. These efforts may include actuator design improvements, such as stacked piezo-electric elements or microfabricated high-turn-number electromagnetic coils, as well as improvements in valve seat design, using soft-seat materials or knife-edge hard seat designs, chip-level integration of valves with driver and power conditioning electronics, and appropriate coatings of valve internal components exposed to propellants to avoid potential valve material erosion concerns.

The design challenges facing the development of a MEMS-valve suitable for applications in space propulsion feed systems may seem daunting. However, the use of MEMS-based design approaches may also provide benefits over more conventional, non-MEMS fabrication techniques that may be exploited in an effort to overcome those challenges. The aforementioned "knife-edge" hard seats, for example, may be manufactured to much smaller dimensions than is possible with conventional fabrication techniques, thus reducing the probability of seat contamination, and reducing actuator force requirements. The tight, on-the-chip integration between valve components and driver/power conditioning circuitry would not be possible using non-microfabrication methods. Finally, chip-to-chip bonding between different flow components, such as MEMS-based thrusters, filters, sensors and valves and the required driver and power conditioning circuitry would allow propulsion modules to be realized that may be substantially smaller than are obtainable with any other fabrication method available today. A microfabricated valve would constitute a keystone in such a design approach, which appears to make the further development of MEMS-based valves well worth the associated technical risks.

VI. ACKNOWLEDGMENTS

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